CLAIMS

1. System for estimating the ground condition under a driving vehicle, comprising:

- a wheel speed sensor (4) for sensing a wheel speed signal ($t(n)$, $\omega(n)$) which is indicative of the wheel speed of a vehicle's wheel driving over the ground (2,3); and
- a first analyser unit (8) coupled to said wheel speed sensor (4) which comprises
  - a sensor imperfection estimation section (9) which is designed to estimate a sensor imperfection signal ($\hat{\delta}_l$) from the wheel speed signal ($t(n)$) which is indicative of the sensor imperfection of the wheel speed sensor (4);
  - a signal correction section (10) which is designed to determine an imperfection-corrected sensor signal ($\varepsilon(n)$) from the wheel speed signal (t_n) and the sensor imperfection signal ($\hat{\delta}_l$); and
  - a ground condition estimation section (11) which is designed to estimate a first estimation value ($r(n)$, $\alpha(n)$) indicative of the ground condition from the imperfection-corrected sensor signal ($\varepsilon(n)$).

2. The system of claim 1, wherein the wheel speed sensor (4) comprises a segmented rotary element (5), and the sensor imperfection estimation section (9) is designed to estimate, at each revolution of the rotary element (5), a sensor imperfection value ($\hat{\delta}_l$) representative of the sensor imperfection signal for each of the segments (6) of the rotary element (5).

3. The system of claim 2, wherein the sensor imperfection value ($\hat{\delta}_l$) is a weighted average of sensor imperfection values ($y(n)$) of previous and current revolutions (n) of the rotary element.

4. The system of one of the preceding claims, wherein the sensor imperfection estimation section (9) comprises a low pass

filter which is implemented according to the following filter relation:

$$LP:\ \hat{\delta}_l = (1-\mu)\hat{\delta}_l + \mu y(n)\ ,$$

with

$$y(n) = \frac{2\pi}{T_{LAP}(n)}(t(n) - t(n-1)) - \frac{2\pi}{L}$$

wherein $\hat{\delta}_l$ is an estimation value of the sensor imperfection, μ is a forgetting factor of the filter, $t(n)$ and $t(n-1)$ is the wheel speed signal, L is the total number of segments (6) of the rotary element (5) and $T_{LAP}(n)$ is the duration of a complete revolution of the rotary element (5).

5. The system of one of the preceding claims, wherein the ground condition estimation section (9) comprises:

- a variance determination section (12) which is designed to determine the variance ($\alpha(n)$) of the imperfection-corrected sensor signal ($\varepsilon(n)$), and
- a ground condition estimation subsection (13) which is designed to estimate the first estimation value ($r(n)$) on the basis of the variance ($\alpha(n)$) thus determined.

6. The system of one of claims 2 to 5, wherein the variance determination section (12) comprises a low pass filter (16) for determining the variance ($\alpha(n)$) of the imperfection-corrected sensor signal ($\varepsilon(n)$) according to the following relation:

$$\alpha(n) = Var(\varepsilon) = LP(\varepsilon^2) - LP(\varepsilon)^2\ ,$$

wherein $LP(\varepsilon)$ is a low pass filtered value of the imperfection-corrected sensor signal ($\varepsilon(n)$) and $LP(\varepsilon^2)$ is a low pass filtered value of the square ($\varepsilon^2(n)$) of the imperfection-corrected sensor signal ($\varepsilon(n)$).

7. The system of claim 6, wherein the low pass filter (16) is implemented according to the following filter relation:

$$LP:\ \alpha(n+1) = (1-\lambda)\alpha(n) + \lambda\varepsilon(n)\ ,$$

wherein α is an estimation value of the variance $Var(\varepsilon)$, λ is a forgetting factor of the filter, and $\varepsilon(n)$ is the imperfection-corrected sensor signal.

8. The system of one of the preceding claims, wherein the ground condition estimation subsection (13) comprises a signal change determination section (14) which is designed to determine signal change values ($CUSUMCounter(n)$) according to the following relation:

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \alpha(n) - Drift, 0), CounterLimit),$$

wherein $\alpha(n)$ is the variance obtained from the variance determination section, and $Drift$ and $CounterLimit$ are tuning parameters.

9. The system of claim 8, wherein the ground condition estimation subsection (13) further comprises a decision section (15) which is designed to compare the signal change values ($CUSUMCounter(n)$) from the signal change determination section (14) with a first and a second threshold value ($set, reset$) and to output a current first estimation value ($r(n)$) indicative of a rough road condition if the current signal change value ($CUSUMCounter(n)$) is greater than the first threshold value (set), a current first estimation value indicative of a normal road condition if the signal change value ($CUSUMCounter(n)$) is lower than the second threshold value ($reset$), and otherwise a current first estimation value equal to the previous first estimation value ($r(n-1)$).

10. The system of one of the preceding claims, which comprises:

- one first analyser unit (8) for each wheel ($i = FL, FR, RL, RR$) of the vehicle having more than one wheel, wherein each first analyser unit (8) is designed to provide a first estimation value ($\alpha_i(n)$) indicative of the ground condition under the respective wheel, and
- a combination section (17) which is designed to combine the first estimation values ($\alpha_i(n)$) provided from each of the

first analyser units (8) in order to obtain a combined first estimation value ($\gamma(n)$, $I_{h1}(n)$) indicative of the road condition under the vehicle.

11. The system of claim 10, wherein the combined first estimation value ($\gamma(n)$, $I_{h1}(n)$) is determined by

- averaging the first estimation values ($\alpha_i(n)$) provided from each of the first analyser units (8),
- using networks of series expansion type, in particular neural networks, radial basis function networks, fuzzy networks, on the basis of the first estimation values ($\alpha_i(n)$),
- using a min-function on the basis of the first estimation values ($\alpha_i(n)$), and/or
- using a max-function on the basis of the first estimation values ($\alpha_i(n)$).

12. The system of claim 10 or 11, in combination with claim 8 or 9, wherein the signal change determination section (14) is coupled to the combination section (17) in order to determine the signal change value ($CUSUMCounter(n)$) on the basis of the combined first estimation value ($\gamma(n)$).

13. The system of one of the preceding claims, further comprising:

- a second analyser unit (19) which is associated with the wheel speed sensor (4) and designed to determine a second estimation value ($\beta(n)$) indicative of the ground condition from the wheel speed signal ($\omega(n)$) received from the wheel speed sensor (4); and
- a decision unit (20) which is designed to determine a combined estimation value ($R(n)$) indicative of the ground condition on the basis of the first and second estimation values ($\alpha(n)$, $\beta(n)$) from the first and second analyser units (8,19), respectively.

14. The system of claim 13, wherein the second analyser unit (19) comprises:

- a band pass or high pass filter section (21) for filtering the wheel speed signal ($\omega(n)$), and a variance estimation section (12) for determining a variance value ($\beta(n)$) from the filtered wheel speed signal ($\tilde{\omega}(n)$), wherein the variance value ($\beta(n)$) is indicative of the ground condition under the respective wheel;
- a side-wise correlation section which is designed to correlate the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a first side of the vehicle (1) with the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a second side of the vehicle (1), wherein the correlation value ($r(n)$) is indicative of the ground condition;
- an axle-wise correlation section which is designed to correlate the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a first axle of the vehicle (1) with the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a second axle of the vehicle (1), wherein the correlation value ($r(n)$) is indicative of the ground condition; or
- a frequency determination section which is designed to determine the highest Fourier frequency ($r(n)$) of the wheel speed signal ($\omega(n)$) which is indicative of the ground condition.

15. The system of claim 13 or 14, comprising:

- one first analyser unit (8) for each wheel ($i = FL, FR, RL, RR$) of the vehicle having more than one wheel, wherein each first analyser unit (8) is designed to provide a first estimation value ($\alpha_i(n)$) indicative of the ground condition under the respective wheel, and
- a first combination section (17) which is designed to combine the first estimation values ($\alpha_i(n)$) provided from each of the first analyser units (8) in order to obtain a

combined first estimation value ($\gamma(n)$) indicative of the road condition under the vehicle;

- a signal change determination section (14) which is designed to determine signal change values ($CUSUMCounter(n)$) on the basis of the combined first estimation values ($\gamma(n)$) according to the following relation:
$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \gamma(n) - Drift, 0), CounterLimit)$,
wherein $Drift$ and $CounterLimit$ are tuning parameters;
- one second analyser unit (19) for each wheel ($i = FL, FR, RL, RR$) of the vehicle, wherein each second analyser unit (19) is designed to provide a second estimation value ($\beta_i(n)$) indicative of the ground condition under the respective wheel, and
- a second combination section (17) which is designed to combine the second estimation values ($\beta_i(n)$) provided from each of the second analyser units (19) in order to obtain a combined second estimation value ($r_2(n)$) indicative of the road condition under the vehicle
- an output combination section (22) for combining the signal change values ($CUSUMCounter(n)$) and the second combined estimation values ($r_2(n)$) in order to obtain a combined estimation value ($\Omega(n)$, $R(n)$) indicative of the road condition under the vehicle.

16. The system of claim 13 or 14, comprising:
- one first analyser unit (8) for each wheel ($i = FL, FR, RL, RR$) of the vehicle having more than one wheel, wherein each first analyser unit (8) is designed to provide a first estimation value ($\alpha_i(n)$) indicative of the ground condition under the respective wheel, and
- a first combination section (17) which is designed to combine the first estimation values ($\alpha_i(n)$) provided from each of the first analyser units (8) in order to obtain a combined first estimation value ($r_1(n)$) indicative of the road condition under the vehicle;

- one second analyser unit (19) for each wheel ($i = FL, FR, RL, RR$) of the vehicle, wherein each second analyser unit (19) is designed to provide a second estimation value ($\beta_i(n)$) indicative of the ground condition under the respective wheel, and
- a second combination section (17) which is designed to combine the second estimation values ($\beta_i(n)$) provided from each of the second analyser units (19) in order to obtain a combined second estimation value ($r_2(n)$) indicative of the road condition under the vehicle
- an output combination section (22) for combining the first and second combined estimation values ($r_1(n)$, $r_2(n)$) in order to obtain a combined estimation value ($\Omega(n)$) indicative of the road condition under the vehicle; and
- a signal change determination section (14) which is designed to determine signal change values ($CUSUMCounter(n)$) on the basis of the combined estimation values ($\Omega(n)$) from the output combination section (22) according to the following relation:

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \Omega(n) - Drift, 0), CounterLimit),$$

wherein $Drift$ and $CounterLimit$ are tuning parameters.

17. The system of claim 15 or 16, further comprising a decision section (15) according to claim 9.

18. Method for estimating the ground condition under a driving vehicle, comprising the steps of:

- sensing a wheel speed signal ($t(n)$, $\omega(n)$) by means of a wheel speed sensor (4) which is indicative of the wheel speed of a vehicle's wheel driving over the ground (2,3); and
- estimating a sensor imperfection signal ($\hat{\delta}_l$) from the wheel speed signal ($t(n)$) which is indicative of the sensor imperfection of the wheel speed sensor (4);

- determining an imperfection-corrected sensor signal ($\varepsilon(n)$) from the wheel speed signal ($t(n)$) and the sensor imperfection signal ($\hat{\delta}_l$); and
- estimating a first estimation value ($r(n)$, $\alpha(n)$) indicative of the ground condition from the imperfection-corrected sensor signal ($\varepsilon(n)$).

19. The method of claim 18, wherein the step of estimating the sensor imperfection signal ($\hat{\delta}_l$) from the wheel speed signal ($t(n)$) comprises estimating, at each revolution of the rotary element (5), a sensor imperfection value ($\hat{\delta}_l$) representative of the sensor imperfection signal for each of the segments (6) of a rotary element (5).

20. The method of claim 19, wherein the sensor imperfection value ($\hat{\delta}_l$) is a weighted average of sensor imperfection values ($y(n)$) of previous and current revolutions (n) of the rotary element.

21. The method of one of the preceding claims, wherein the step of estimating the sensor imperfection signal ($\hat{\delta}_l$) from the wheel speed signal ($t(n)$) comprises a step of low pass filtering according to the following filter relation:

$$LP: \ \hat{\delta}_l = (1-\mu)\hat{\delta}_l + \mu y(n) \text{ ,}$$

wherein

$$y(n) = \frac{2\pi}{T_{LAP}(n)}(t(n) - t(n-1)) - \frac{2\pi}{L}$$

wherein $\hat{\delta}_l$ is an estimation value of the sensor imperfection, μ is a forgetting factor of the filter, $t(n)$ and $t(n-1)$ is the wheel speed signal, L is the total number of segments (6) of the rotary element (5) and $T_{LAP}(n)$ is the duration of a complete revolution of the rotary element (5).

22. The method of one of the preceding claims, further comprising the steps of:
- determining a variance ($\alpha(n)$) of the imperfection-corrected sensor signal ($\varepsilon(n)$), and
- estimating the first estimation value ($r(n)$) on the basis of the variance ($\alpha(n)$) thus determined.

23. The method of one of claims 19 to 22, wherein the step of determining a variance ($\alpha(n)$) of the imperfection-corrected sensor signal ($\varepsilon(n)$) comprises the step of low pass filtering the imperfection-corrected sensor signal ($\varepsilon(n)$) according to the following relation:

$$\alpha(n) = Var(\varepsilon) = LP(\varepsilon^2) - LP(\varepsilon)^2 ,$$

wherein $LP(\varepsilon)$ is a low pass filtered value of the imperfection-corrected sensor signal ($\varepsilon(n)$) and $LP(\varepsilon^2)$ is a low pass filtered value of the square ($\varepsilon^2(n)$) of the imperfection-corrected sensor signal ($\varepsilon(n)$).

24. The method of claim 23, wherein the low pass filtering is implemented according to the following filter relation:

$$LP: \ \alpha(n+1) = (1-\lambda)\alpha(n) + \lambda\varepsilon(n) ,$$

wherein α is an estimation value of the variance $Var(\varepsilon)$, λ is a forgetting factor of the filter, and $\varepsilon(n)$ is the imperfection-corrected sensor signal.

25. The method of one of the preceding claims, further comprising the step of determining signal change values ($CUSUMCounter(n)$) according to the following relation:

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \alpha(n) - Drift, 0), CounterLimit) ,$$

wherein $\alpha(n)$ is the variance obtained from the variance determination section, and $Drift$ and $CounterLimit$ are tuning parameters.

26. The method of claim 25, further comprising to compare the signal change values ($CUSUMCounter(n)$) with a first and a second

threshold value ($set, reset$) and to output a current first estimation value ($r(n)$) indicative of a rough road condition if the current signal change value ($CUSUMCounter(n)$) is greater than the first threshold value (set), a current first estimation value indicative of a normal road condition if the signal change value ($CUSUMCounter(n)$) is lower than the second threshold value ($reset$), and otherwise a current first estimation value equal to the previous first estimation value ($r(n-1)$).

27. The method of one of the preceding claims, further comprising:

- providing a first estimation value ($\alpha_i(n)$) indicative of the ground condition under the respective wheel for each wheel ($i = FL, FR, RL, RR$) of the vehicle having more than one wheel, and
- combining the first estimation values ($\alpha_i(n)$) in order to obtain a combined first estimation value ($\gamma(n)$, $I_{h1}(n)$) indicative of the road condition under the vehicle.

28. The method of claim 27, wherein the combined first estimation value ($\gamma(n)$, $I_{h1}(n)$) is determined by

- averaging the first estimation values ($\alpha_i(n)$) provided from each of the first analyser units (8),
- using networks of series expansion type, in particular neural networks, radial basis function networks, fuzzy networks, on the basis of the first estimation values ($\alpha_i(n)$),
- using a min-function on the basis of the first estimation values ($\alpha_i(n)$), and/or
- using a max-function on the basis of the first estimation values ($\alpha_i(n)$).

29. The method of claim 27 or 28, in combination with claim 8 or 9, wherein a signal change value ($CUSUMCounter(n)$) is determined on the basis of the combined first estimation value ($\gamma(n)$).

30. The method of one of the preceding claims, further comprising:
- determine a second estimation value ($\beta(n)$) indicative of the ground condition from the wheel speed signal ($\omega(n)$) received from the wheel speed sensor (4); and
- determining a combined estimation value ($R(n)$) indicative of the ground condition on the basis of the first and second estimation values ($\alpha(n)$, $\beta(n)$).

31. The method of claim 30, further comprising:
- filtering the wheel speed signal ($\omega(n)$) with a band pass or high pass filter, and determining a variance value ($\beta(n)$) from the filtered wheel speed signal ($\tilde{\omega}(n)$), wherein the variance value ($\beta(n)$) is indicative of the ground condition under the respective wheel;
- correlating the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a first side of the vehicle (1) with the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a second side of the vehicle (1), wherein the correlation value ($r(n)$) is indicative of the ground condition;
- correlating the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a first axle of the vehicle (1) with the wheel speed signals ($\omega(n)$) of the wheels ($i = FL, FR, RL, RR$) on a second axle of the vehicle (1), wherein the correlation value ($r(n)$) is indicative of the ground condition; or
- determining the highest Fourier frequency ($r(n)$) of the wheel speed signal ($\omega(n)$) which is indicative of the ground condition.

32. The method of claim 30 or 31, comprising the steps of:
- providing a first estimation value ($\alpha_i(n)$) indicative of the ground condition under the respective wheel, for each wheel ($i = FL, FR, RL, RR$) of the vehicle having more than one wheel; and

- combining the first estimation values ($\alpha_i(n)$) in order to obtain a combined first estimation value ($\gamma(n)$) indicative of the road condition under the vehicle;
- determining signal change values ($CUSUMCounter(n)$) on the basis of the combined first estimation values ($\gamma(n)$) according to the following relation:
$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \gamma(n) - Drift, 0), CounterLimit)$,
wherein $Drift$ and $CounterLimit$ are tuning parameters;
- providing a second estimation value ($\beta_i(n)$) indicative of the ground condition under the respective wheel, for each wheel ($i = FL, FR, RL, RR$) of the vehicle; and
- combining the second estimation values ($\beta_i(n)$) in order to obtain a combined second estimation value ($r_2(n)$) indicative of the road condition under the vehicle;
- combining the signal change values ($CUSUMCounter(n)$) and the second combined estimation values ($r_2(n)$) in order to obtain a combined estimation value ($\Omega(n)$, $R(n)$) indicative of the road condition under the vehicle.

33. The method of claim 30 or 31, comprising:
- for each wheel ($i = FL, FR, RL, RR$) of the vehicle having more than one wheel, providing a first estimation value ($\alpha_i(n)$) indicative of the ground condition under the respective wheel; and
- combining the first estimation values ($\alpha_i(n)$) in order to obtain a combined first estimation value ($r_1(n)$) indicative of the road condition under the vehicle;
- for each wheel ($i = FL, FR, RL, RR$) of the vehicle, providing a second estimation value ($\beta_i(n)$) indicative of the ground condition under the respective wheel; and
- combining the second estimation values ($\beta_i(n)$) in order to obtain a combined second estimation value ($r_2(n)$) indicative of the road condition under the vehicle

- combining the first and second combined estimation values ($r_1(n)$, $r_2(n)$) in order to obtain a combined estimation value ($\Omega(n)$) indicative of the road condition under the vehicle; and
- determining signal change values ($CUSUMCounter(n)$) on the basis of the combined estimation values ($\Omega(n)$) according to the following relation:
$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \Omega(n) - Drift, 0), CounterLimit)$$
, wherein $Drift$ and $CounterLimit$ are tuning parameters.

34. The method of claims 32 or 33, further comprising the steps of claim 26.

35. A computer program including program code for carrying out a method, when executed on a processing system, of estimating the ground condition under a driving vehicle, the method comprising the steps of:
- sensing a wheel speed signal ($t(n)$, $\omega(n)$) by means of a wheel speed sensor (4) which is indicative of the wheel speed of a vehicle's wheel driving over the ground (2,3); and
- estimating a sensor imperfection signal ($\hat{\delta}_l$) from the wheel speed signal ($t(n)$) which is indicative of the sensor imperfection of the wheel speed sensor (4);
- determining an imperfection-corrected sensor signal ($\varepsilon(n)$) from the wheel speed signal ($t(n)$) and the sensor imperfection signal ($\hat{\delta}_l$); and
- estimating a first estimation value ($r(n)$, $\alpha(n)$) indicative of the ground condition from the imperfection-corrected sensor signal ($\varepsilon(n)$).